Reports

Use of the Space Shuttle for Remote Sensing Research: Recent Results and Future Prospects

Abstract. *Routine access to low earth orbit provided by the space shuttle holds great potential for global studies of the earth's resources and its environment. A successful test flight of the Columbia orbiter in November 1981 demonstrated the utility and versatility of the shuttle for earth-related research. A series of remote sensing experiments is currently planned for the mid-1980's that will more fully exploit the shuttle's earth observation capabilities.*

The first cargo carried into orbit on the space shuttle was a set of scientific experiments that are collectively referred to as the OSTA-1 payload (after NASA's former Office of Space and Terrestrial Applications). These experiments were designed to obtain remote sensing measurements of the earth that could be applied to the study of marine biology, atmospheric chemistry, meteorology, and continental geology. They were placed on the second shuttle test flight to provide an early demonstration of the shuttle's ability to conduct earth-related research. The objectives and characteristics of the OSTA-1 experiments have been described (*1*). In this report we summarize the outcome of the OSTA-1 mission and discuss the prospects for future shuttle-based remote sensing experiments.

The second test flight of the space shuttle represented the first time that a manned spacecraft was relaunched after an earlier orbital mission. The test flight was originally scheduled for 9 October 1981. However, a series of technical problems delayed the launch, and the shuttle lifted off from the Kennedy Space Center in Florida at 10:10 a.m. Eastern Standard Time on 12 November 1981. After a series of maneuvers, it was placed in a near-circular orbit at an average altitude of 262 km and circled the earth at this altitude every 90 minutes. The orbit was inclined 38° with respect to the earth's equator, which meant that the shuttle's flight path was confined to the latitude band 38°S to 38°N. The shuttle was placed in an earth-viewing orientation throughout much of the flight so that the instruments in the payload bay directly faced the earth's surface (Fig. 1).

A technical problem developed early in the mission involving the three hydrogen fuel cells that produce electrical power onboard the shuttle. One of these units was shut down completely and another failed to perform as expected. Special procedures were invoked to monitor and manage the electrical output of the two functioning cells. At the same time, revised weather forecasts for southern California indicated that local weather conditions at the prime landing site would deteriorate during the flight. For these reasons, it was decided to shorten the mission from the planned duration of 124 hours to a total of 54 hours. The shuttle landed at NASA's Dryden Research Facility in California on 14 November (1:23 p.m. Pacific Standard Time) after completing 36 orbits of the earth. The principal investigators for the OSTA-1 experiments were at Johnson Space Center in Texas throughout the mission. The decision to shorten the test flight necessitated a great deal of spontaneous replanning in a very dynamic and sometimes uncertain environment.

The delayed launch and limited duration of the second test flight affected both the quality and quantity of the data collected by the individual OSTA-1 experiments. Solar illumination conditions changed significantly during October and November, particularly at higher latitudes. In addition, weather conditions in the Northern Hemisphere tended to worsen during the late fall. Experiment plans that had been developed before the flight were altered significantly when the mission was abbreviated. In many instances, criteria employed in targeting specific areas for data collection were not as selective as those that would have been employed during the nominal mission. The outcome of each of the OSTA-1 experiments is summarized below.

Shuttle imaging radar A (SIR-A). SIR-A was a side-looking, synthetic aperture radar that artificially illuminated the earth's surface with horizontally polarized microwave radiation transmitted at *L*-band frequency (corresponding to a wavelength of 23 cm). Approximately 10 million square kilometers of radar imagery were acquired by SIR-A with a ground resolution of 40 m. Coverage was obtained over all of the major continental areas beneath the shuttle's flight path. Due to the change in mission duration, more coverage was obtained over marine areas than was originally planned. The signal-to-noise characteristics of the SIR-A system exceeded expectations, and unanticipated subtle variations in radar backscatter were detected over ocean surfaces.

One unexpected result of the SIR-A experiment was the discovery of buried stream channels and other subsurface drainage features in radar imagery of the eastern Sahara desert. Soil moisture normally attenuates microwave radiation over depths of a few centimeters. In regions such as northern Africa, however, surface soils are extremely dry and their effective attenuation is low. SIR-A showed that radar penetration can be achieved in these materials to depths of several meters. The ability to map ancient drainage features in arid environments has implications for the study of long-term climatic change, ancient civilizations, and the resource potential of desert areas.

Comparison of SIR-A data with radar imagery acquired by Seasat in 1978 provided new insight into the backscattering characteristics of natural terrain. The principal difference between these systems is that Seasat illuminated the surface at a 20° incidence angle (as measured from the vertical), whereas SIR-A illuminated the surface at 50°. Radar backscatter from natural terrain is primarily governed by variations in surface slope at smaller angles of incidence and by surface roughness at larger angles (typically greater than 30°). Large-scale variations in backscatter observed in Seasat and SIR-A imagery of the same area can be directly related to variations in topographic relief and surface roughness. Backscatter differences were also detected in imagery of relatively smooth, flat areas and are probably related to seasonal variations in soil moisture conditions.

Shuttle multispectral infrared radiometer (SMIRR). SMIRR was a nonimaging sensor that measured the intensity of

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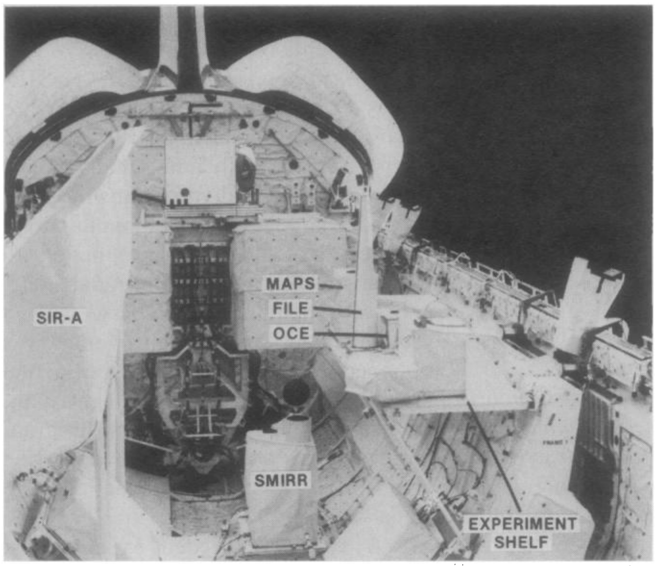

Fig. 1. View of the space shuttle Columbia's payload bay during the second shuttle test flight. The earth is at the top of the picture and the payload bay is completely illuminated by earthshine. Sensor acronyms are defined in the text. The black circle near the center is the underside of the SMIRR telescope cap.

solar radiation reflected from the earth's surface in ten discrete spectral bands. Five SMIRR channels were at wavelengths of 2.0 to 2.4 μm, where many common minerals have diagnostic spectral absorption features. The SMIRR experiment was designed primarily to determine whether these absorption features could be detected in multispectral surveys of natural terrain performed through the earth's atmosphere.

Roughly 60 percent of the SMIRR data acquired during the mission were obtained under cloud-free conditions. Excellent coverage was obtained over portions of Mexico, Spain, northern Africa, the Middle East, and China. Soil and rock samples that had been collected in southeast Egypt were made available to the principal investigators, and initial data analysis efforts have concentrated on this area. The reflectance properties of these surface samples were measured in the laboratory and directly compared with orbital SMIRR data. Preliminary results indicate that carbonate minerals can be discriminated from hydroxyl-bearing clay minerals on the basis of reflectance at 2.0 to 2.4 μm. Furthermore, subtle variations in surface reflectivity detected in the SMIRR measurements may permit geologists to distinguish specific types of clay minerals such as kaolinite $[Al_2Si_2O_5(OH)_4]$ and montmorillonite $[Al_2Si_4O_{10}(OH)_2 \cdot nH_2O]$. The results demonstrate a need for more channels and improved spectral resolution in future generations of orbital multispectral scanners.

Measurement of air pollution from satellites (MAPS). The MAPS experiment consisted of a two-channel gas filter radiometer that measured the intensity of upwelling thermal radiation at a wavelength of 4.67 μm. The instrument was designed to determine the concentration of CO in the earth's atmosphere at ambient pressures of 266 and 76 torr (corresponding roughly to altitudes of 7.5 and 11 km, respectively). Useful data were obtained over more than 38,000 km of the shuttle's flight path. Coverage was fairly evenly distributed around the world between latitudes of ±38°. The signal-to-noise characteristics of the sensor exceeded expectations, and pronounced gradients in CO abundance were detected along individual orbital passes.

Contemporaneous measurements of CO abundance were obtained during the mission with an airborne version of the MAPS radiometer and in situ sampling techniques. Initial analysis has focused on a comparison of orbital and aerial data obtained over the eastern United States. Mixing ratios of CO inferred from orbital measurements are approximately 50 percent greater than those inferred from airborne measurements. A comparison of the raw data suggests that this discrepancy may be attributable to a calibration error in the shuttle sensor. Consequently, the orbital version of the instrument has been returned to the laboratory, where it is undergoing a series of calibration tests. The entire MAPS data set will be reduced to produce the first global map of CO abundance at lower latitudes after these tests are completed.

Ocean color experiment (OCE). OCE employed an eight-channel multispectral imaging sensor to measure solar radiation reflected from ocean surfaces at wavelengths of 0.4 to 0.8 μm. This instrument is similar to the coastal zone color scanner on the Nimbus-7 satellite. The shuttle OCE was designed to detect variations in the pigmentation of ocean surface waters that are related to the presence of chlorophyll in phytoplankton. Interpretation of coastal multispectral surveys in terms of phytoplankton abundance is complicated by reflectivity variations associated with shoals and suspended sediments that are not present in the open ocean.

Launch delays had a major impact on OCE data collection plans. Solar zenith angles at prime target sites were less than optimum, and the original plans for in situ phytoplankton measurements by oceanographic research vessels had to be modified. Useful data were obtained over the Mediterranean and Yellow seas. In particular, reflectivity variations observed over the Strait of Gibraltar during successive shuttle passes have been used to estimate the direction and velocity of surface currents near the entrance to the Mediterranean.

The OCE experiment demonstrated the feasibility of mapping chlorophyll concentration in the open ocean. This capability could be used to monitor global changes in phytoplankton abundance from space. Phytoplankton are a key building block at the base of the earth's food chain, and information on their distribution and total abundance could be important in long-term studies of global ecology.

Feature identification and location experiment (FILE). FILE was a proof-of-concept experiment in which data from two imaging cameras were used to classify surface materials into one of four categories: water, vegetation, bare ground, or clouds and snow. Each camera contained a two-dimensional array of charge-coupled detectors (100 by 100 elements). They were designed to measure surface reflectivity at wavelengths of 0.65 and 0.85 μm. Similar sensors may be placed on future satellites to control the operation of other earth imaging instruments and avoid the collection of unwanted or unusable data.

FILE was a nadir-viewing sensor with a total field of view of roughly 80 by 110 km. Its classification algorithms were designed for evaluating landscape conditions under circumstances where the angle between the shuttle's orbital plane and the earth-sun line (commonly referred to as the beta angle) was small. Unfortunately, deviations from the original mission plan resulted in relatively high beta angles throughout much of the test flight. In addition, data recording capabilities for FILE were compromised by an error in the initial setting of the experiment's onboard tape recorder. A limited amount of data was collected. However, these data did not provide a fair test of FILE's classification logic and it was not possible to fully evaluate the utility of FILE-type sensors for automated command and control of earth imaging satellites.

Night/day optical survey of lightning (NOSL). The purpose of the NOSL experiment was to obtain motion picture images of large-scale lightning discharges within the atmosphere under both day and night conditions. A 16-mm camera with an associated photocell sensor and diffraction grating was used to study the periodicity and spectral characteristics of lightning discharges. This equipment was stowed in the aft crew compartment and was designed to be operated manually by a crew member. The crew was not able to devote sufficient time to the NOSL experiment during the abbreviated mission, and a very limited amount of data was collected. This experiment was successfully reflown on the fourth shuttle test flight.

Heflex bioengineering test (HBT). The HBT was a precursor study for a plant growth experiment that will be performed on Spacelab 1 in the fall of 1983. It was a passive experiment designed to determine the optimum soil moisture conditions for seed germination under weightless conditions. The HBT consisted of a collection of sealed vials containing dwarf sunflower (*Helianthus annus*) seeds planted in a common type of soil with variable amounts of water. The vials were placed in a container, which was stowed in the aft compartment. There was insufficient time during the abbreviated mission for the HBT seeds to germinate. This experiment was successfully reflown on a subsequent test flight.

OSTA-1 data availability. Data collected by the SIR-A, SMIRR, MAPS, and OCE experiments will be stored at the National Space Science Data Center (NSSDC) for public dissemination (*2*). SIR-A radar imagery is available in the form of photographic prints and transparencies. OCE imagery is available in digital form on computer-compatible tapes. MAPS and SMIRR data will be sent to NSSDC later this year and will be available in digital form. In addition, interested investigators can obtain photographic mosaics that display the exact path of the SMIRR ground track at the earth's surface.

Future experiments. Based in part on the results of the OSTA-1 mission, NASA is planning another series of remote sensing experiments that will tentatively be conducted in August 1984 on the seventeenth flight of the space shuttle. The experiment payload for this mission will consist of an upgraded version of the shuttle imaging radar (SIR-B), a large format camera (LFC), and the MAPS and FILE sensors. These experiments will be placed into an orbit with a 57° inclination and will remain in space for a minimum of 7 days.

The SIR-B system will operate at the same frequency and polarization as SIR-A. However, the SIR-B antenna will be modified so that it can be mechanically rotated while the shuttle's payload bay is facing the earth. This will enable researchers to obtain radar imagery of a specific area at multiple angles of incidence during successive shuttle orbits. Multiple-incidence-angle radar imagery can potentially be used to distinguish surface materials on the basis of their roughness characteristics, in much the same way that multispectral imagery is used to discriminate materials on the basis of their reflectance properties. Similar experiments have not been attempted with airborne radar systems because of the large variation in incidence angle that occurs across a single image swath. Orbital radar systems can illuminate large surface areas at a nearly uniform angle of incidence.

The LFC is a photographic camera with a 305-mm focal length, an *f*/6 aperture, and a film format of 23 by 46 cm. The camera's film platen will move horizontally along the shuttle's line of flight when the shutter is open to minimize smearing effects. A ground resolution of 10 m or better will be achievable at altitudes of 200 to 250 km with standard photographic films. The LFC will be able to obtain overlapping stereoscopic coverage along the shuttle's flight path with base to height ratios of 0.3, 0.6, 0.9, and 1.2. Its imagery should be applicable to cartographic mapping at a scale of 1:50,000.

FILE will be modified slightly and reflown in 1984 to obtain data under more appropriate solar illumination conditions (lower beta angles). The MAPS experiment will also be reflown, largely in its present form, to study seasonal variations in CO abundance in the Northern and Southern Hemispheres. A successor to the SMIRR experiment that would enable researchers to acquire multispectral imagery with a spectral resolution of 20 nm has been proposed; this imaging spectrometer could be flown on a later shuttle flight in the middle to late 1980's.

European scientists are also planning to exploit the shuttle's capabilities for remote sensing experimentation. Spacelab 1 will carry an *X*-band radar system, which will acquire a limited amount of imagery over an 8.5-km swath. In addition, Spacelab 1 will contain a metric camera that can be used for cartographic mapping. Later flights will carry a two-channel modular optoelectronic multispectral scanner (MOMS) into orbit. The MOMS instrument will be the first orbital test of linear detector array technology in an earth imaging sensor system.

Summary. The OSTA-1 mission has demonstrated the shuttle's versatility as an experimental platform for remote sensing research. Three experiments (SIR-A, SMIRR, and OCE) performed flawlessly. A possible error in the calibration of the MAPS sensor was detected during postflight data analysis, and the instrument is now being tested to evaluate its performance in space. The FILE, NOSL, and HBT experiments were compromised by launch delays and the reduced duration of the second shuttle test flight. All three of these experiments were rescheduled for flight on later missions. In addition, the SIR-A system is being mechanically modified to acquire radar imagery at multiple antenna depression angles. The upgraded SIR-B system will return to space in 1984.

In the past, it has not been possible to recalibrate, refurbish, or upgrade experimental sensors that have been placed in orbit around the earth. The shuttle's ability to carry instruments into space routinely and return them to the ground adds a new dimension to the development of remote sensing techniques.

The OSTA-1 mission has also demonstrated how the shuttle can be employed for scientific studies of the earth and its environment. For land remote sensing, the shuttle provides a convenient means of collecting experimental data over prespecified test sites distributed throughout the world. For atmospheric and oceanographic studies, it can be used to survey global environmental conditions at a particular point in time. The shuttle is an efficient and effective platform for remote sensing experimentation, and its use in this capacity is likely to grow significantly during the 1980's.

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References and Notes

1. J. V. Taranik and M. Settle, *Science* **214**, 619 (1981).
2. Further information about the characteristics and availability of OSTA-1 data can be obtained by contacting the National Space Science Data Center, Code 601, NASA-Goddard Space Flight Center, Greenbelt, Md. 20771.

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